

***Gaia* and σ Orionis from $20 M_{\odot}$ to $3 M_{\text{Jup}}$: the most complete and precise Initial Mass Function with a parallax determination?**

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Abstract

The σ Orionis cluster is to date the star-forming region with the largest number of confirmed brown dwarfs and substellar objects below the deuterium burning mass limit. The most massive star, σ Ori Aa, just in the cluster centre, is the $\sim 20 M_{\odot}$ -mass O9.5V star that illuminates the Horsehead Nebula, while the least massive object yet reported, S Ori 70, is only around $3 M_{\text{Jup}}$. In the middle, there is a continuum of stars and substellar objects of all types (including magnetically active B2Vp stars, Herbig-Haro objects, FU Ori stars or T Tauri brown dwarfs) that makes the cluster a cornerstone in the study of the initial mass function, disc presence, X-ray emission or accretion at all mass domains. However, the derived masses strongly depend on the actual heliocentric distance to the cluster. *Gaia* will solve the dilemma.

1 σ Orionis: significance

The σ Orionis cluster ($\tau \sim 3$ Ma, $d \sim 385$ pc, $A_V < 0.3$ mag) is located in the easternmost part of the Ori OB1b association and is one of the most attractive and visited regions for night sky observers (Garrison 1967; Wolk 1996; Walter et al. 2008; Caballero 2008b). The cluster gets the name from the homonymous massive star system in its centre, which is the fourth brightest star in the Orion Belt. The σ Orionis cluster is important for several reasons:

- Its stars illuminate the Horsehead Nebula photodissociation region (Pound et al. 2003; Pety et al. 2005; Goicoechea et al. 2006).
- It contains an abundant X-ray emitter population (Franciosini et al. 2006; Skinner et al. 2008; Caballero et al. 2010).

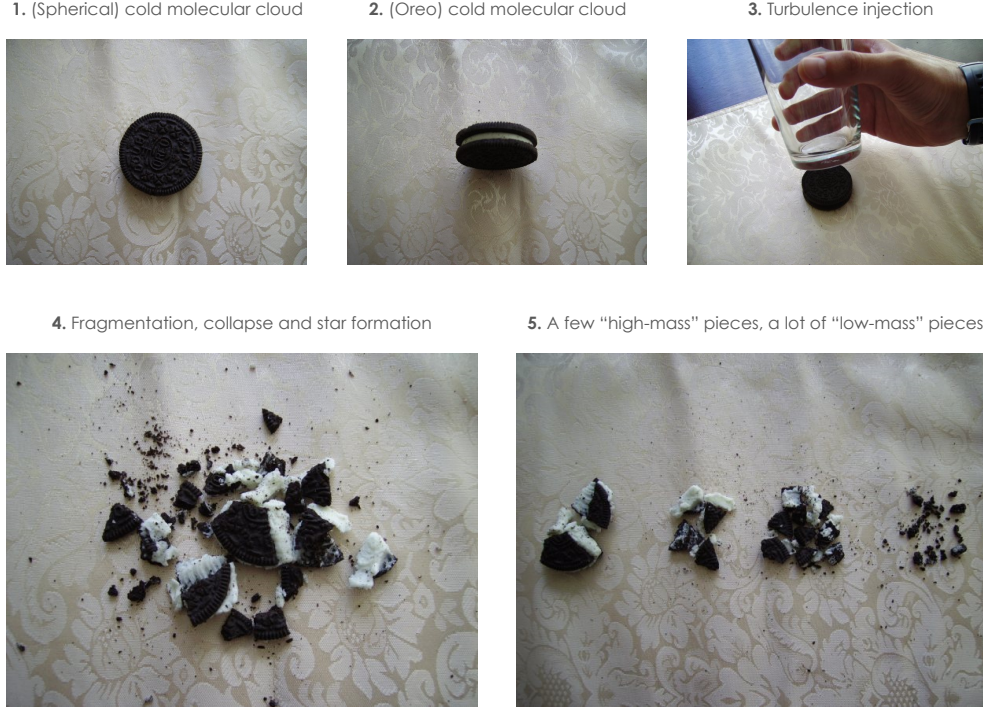


Figure 1: Pictorial sketch of the star formation process and cluster IMF determination (the original idea of breaking into pieces, “fragmenting”, a cookie and counting the pieces was first stated by V. J. S. Béjar; all pieces were eaten after the making of this figure).

- It is a cornerstone for studying disc frequency at $\tau \sim 3$ Ma at all mass domains (Oliveira et al. 2004; Caballero et al. 2007; Zapatero Osorio et al. 2007; Luhman et al. 2008).
- The helium-rich, magnetically active, B2Vp star σ Ori E is in its centre (Walborn 1974; Groote & Hunger 1982; Townsend et al. 2005).
- It holds four Herbig-Haro objects and dozens Herbig Ae/Be, T Tauri and FU Ori stars (Haro & Moreno 1953; Reipurth et al. 1998; Andrews et al. 2004).
- The central star system is the most massive “binary” with an astrometric orbit (Hartkopf et al. 1996; Mason et al. 1998; Caballero 2008a).
- Its proximity, youth and low extinction facilitate studies of accretion rates and frequency at low masses (Scholz & Eislöffel 2004; Kenyon et al. 2005; Gatti et al. 2008).
- It is the star-forming region with the largest number of confirmed brown dwarfs ($M < 70 M_{\text{Jup}}$) and objects below the deuterium burning mass limit (i.e., isolated planetary-mass objects; $M < 13 M_{\text{Jup}}$) with spectroscopy and youth features, e.g., Li I absorption, $\text{H}\alpha$ and X-rays emission, infrared excess, radial velocity (Béjar et al. 1999; Zapatero Osorio et al. 2000; Barrado y Navascués et al. 2001; Rigliaco et al. 2011).

Table 1: IMF works in the σ Orionis cluster.

Work	Mass interval [M_{\odot}]	α	Colour in Fig. 2
Béjar et al. 2001	0.1–0.015	+0.6	Red
Tej et al. 2002	0.45–0.025	+1.2	Orange (dashed)
Sherry et al. 2004	0.2–1.0	+2.7	Not drawn
Caballero 2006, 2010a	3–0.6	+1.4	Yellow
	0.4–0.006	+0.4	Yellow
González-García et al. 2006	0.072–0.007	+0.6	Not drawn
Caballero 2007	18–1.5	+2.0	Green
Caballero et al. 2007	0.11–0.006	+0.6	Not drawn
	0.072–0.006	+0.4	Light blue
Lodieu et al. 2009	0.49–0.010	+0.5	Blue (dashed)
Bihain et al. 2009	0.012–0.0035	+0.0	Dark blue
Caballero 2009	20–1	+2.3	Magenta
	0.3–0.035	+0.3	Magenta

2 σ Orionis: previous IMF works

The abundance of known substellar objects has led σ Orionis to become a key region all over the sky to study the initial mass function (IMF), especially at *very* low masses. The IMF is the empirical function that describes the mass distribution (the histogram of stellar masses) of a population of recently-born stars, and its determination in a cluster is illustrated in Fig. 1.

The behaviour of the IMF has been described repeatedly (e.g., Kroupa 2002), but σ Orionis is probably the cluster where the IMF studies have gone lowest in mass with completeness and confidence, perhaps in more detail than in the Pleiades or the Orion Nebula Cluster. In Table 1, I summarise all IMF works on σ Orionis. I tabulate the mass interval and the corresponding α index in the mass spectrum, $\Delta N/\Delta N = AM^{-\alpha}$ ($\alpha \equiv -\gamma \equiv 1 - \Gamma$). The general trend indicates a Salpeter’s-like slope between 20 and $1 M_{\odot}$ ($\alpha \sim +2.35$), a rather flat mass spectrum ($\alpha \sim +0.3$) between 0.3 and $0.006 M_{\odot}$ ($6 M_{\text{Jup}}$) and a soft elbow in between, at $1\text{--}0.3 M_{\odot}$. The mass spectrum may go *down* at a few Jupiter masses after the results exposed by Peña Ramírez et al. (2011). See Fig. 2.

3 σ Orionis: what to do next?

There are some caveats in the IMF determination in σ Orionis:

- The IMF relies on cluster parameters and on the used theoretical models. But which models to use? How to handle uncertainties at young ages? Which band or combination of bands to use? Are colour-dependent bolometric corrections better than apparent magnitudes only? How to match different isochrones of different authors valid at different mass and effective temperature intervals?

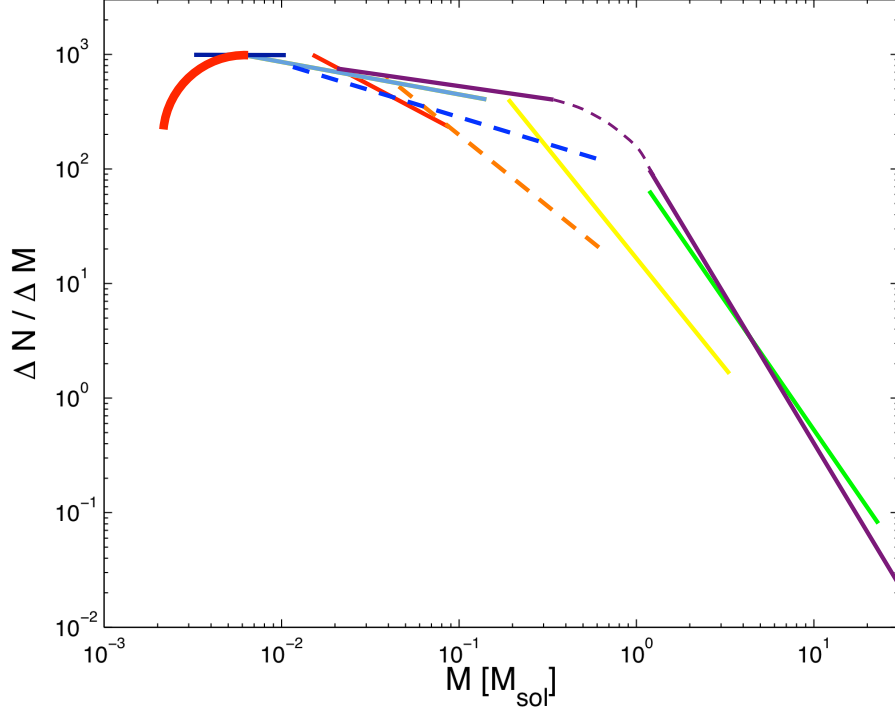


Figure 2: Some mass spectra reported in the σ Orionis cluster (see Table 1 for the references and colour code).

- How old is σ Orionis? There have been reports of ages from 1 to 10 Ma, with a general consensus towards the 2–4 Ma interval, being 3 Ma the canonical value. But what if it is slightly older or younger? Is there any age spread? How do we account for the different accretion history?
- What is the contamination rate in the cluster? In σ Orionis, there is contamination by B stars in nearby star-forming regions in Ori OB1b, foreground low proper-motion AFG dwarfs, background giants, field late-M-, L- and T-type stars and brown dwarfs, red quasars... Spectroscopy, astrometry and methane imaging help disentangling actual cluster members from interlopers (Sacco et al. 2008; Caballero et al. 2008; Caballero 2010b; Peña Ramírez et al. 2011).
- What is the “system IMF”? Further binarity studies at all mass and separation domains are required. Some surprises await us, such as the confirmation that the σ Ori star itself is not only an astrometric binary, but also a *massive spectroscopic triple* containing an O9.5V, a B0.5V and an early B dwarf (Simón-Díaz et al., this volume).
- Is there a cut-off of the IMF below $0.006 M_{\odot}$? To ascertain it, there is no other way than performing ultra-deep imaging ($I > 26$ mag, $J > 22$ mag, $H > 22$ mag) in an area wider than 1000 arcmin^2 with methane, astrometric and spectroscopic follow-up of

T-type candidates, which requires a strong observational effort.

- What is the distance to σ Orionis? Is it 350 pc (*Hipparcos*, with large error bars), 450 pc (Sherry et al. 2008), or something in between at around 400 pc (Caballero 2008a; Mayne & Naylor 2008)? Solution: *Gaia*!

Gaia will likely not detect cluster brown dwarfs ($J > 14.5$ mag), and some cluster dynamical studies (radial velocities, proper motions) will arrive earlier than the ESA mission, but *Gaia* will measure the parameter with the largest error contribution to the IMF, *distance*, from accurate parallax determination. A list of dozens of confirmed cluster members with $V < 20$ mag is easy to accomplish; we only need to wait a couple of years.

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